state get mixed before emission. Such a mixing process may be explained by the assumption that the equilibrium position of the excited state occurs at the T_d site symmetry point of the crystal.

Using these ideas and the data obtained from the luminescence width, we have constructed parabolic configuration-coordinate curves for the ground and localized excited state of the center. These are shown in Fig. 12. In determining these curves we have assumed an excited-state vibrational mass corresponding to the symmetric breathing-mode vibration. The emission peak shift with temperature and the displacement of the two minima from one another are then predictable. The predicted emission peak shift is 1.2×10^{-4} eV/K, while the measured shift is 0.86×10^{-4} eV/K. If we assume that the particular configuration coordinate is the distortion of the tetrahedron from T_d to C_{3v} as observed in EPR, a comparison can be made of this distortion as deduced by EPR and by the configuration-coordinate description. Both values are approximately 0.5 Å. The configuration-coordinate model also explains, at least qualitatively, the difference between the optical and the thermal activation energies for quenching the 1.9-eV luminescence since the model should apply equally well to excited-hole states of the P_{Se} center. These excited states are expected to lie very close to the valence band edge, as evidenced by the fact that infrared radiation produces free holes leading to p-type conductivity. The excited-hole states are expected to be more nearly cubic than the ground state, leading to a displacement in the equilibrium positions and a difference between the thermal and optical activation energies.

The nature of the center responsible for the 1.15-eV luminescence remains obscure. An interesting possibility is that it arises from an electronic transition of the ionized P_{Se} center, i.e., P'_{Se}. The variable intensity of this luminescence with post-growth annealing and the absorption band which is produced by band-gap radiation are qualitatively in agreement with this supposition, but substantiating evidence is not available.

ACKNOWLEDGMENTS

The authors wish to acknowledge the able technical assistance of R. Stinedurf and E. Ruthven.

*Research sponsored in part by the Air Force Office of Scientific Research Contract No. F44620-67-C-0073.

[1]R. K. Watts, W. C. Holton, and M. de Wit, preceding paper, Phys. Rev. B 3, 404 (1971).

[2]The defect notation used in this paper follows the convention established by F. A. Kröger and H. J. Vink, Solid State Phys. 3, 307 (1956).

[3]G. B. Stringfellow and R. H. Bube, Phys. Rev. 171, 903 (1968).

[4]W. C. Holton, M. de Wit, R. K. Watts, and T. L. Estle, J. Phys. Chem. Solids 30, 963 (1969).

[5]W. C. Holton, M. de Wit, and T. L. Estle, in *International Symposium on Luminescence, The Physics and Chemistry of Scintillators*, edited by N. Riehl and H. Kallmann (Karl Thiemig, Munich, 1966), p. 455.

[6]W. C. Holton, R. K. Watts, and R. D. Stinedurf, J. Cryst. Growth 6, 97 (1969).

[7]M. Aven and W. Garwicki, J. Electrochem. Soc. 114, 1063 (1967).

[8]D. Curie and J. S. Prenner, in *Physics and Chemistry of II-VI Compounds*, edited by M. Aven and J. S. Prenner (Wiley, New York, 1967), p. 440.

PHYSICAL REVIEW B VOLUME 3, NUMBER 2 15 JANUARY 1971

Hot-Electron Transfer in Gallium Antimonide from Infrared Faraday Effect*

H. Heinrich
Institut für Angewandte Physik der Universität. A-1090 Vienna, Austria
and Ludwig-Boltzmann Institut für Festkörperphysik, Vienna, Austria
(Received 27 July 1970)

Measurements of the infrared Faraday effect at 3.39 μm have been performed to obtain information about the carrier transfer between the Γ_1 and L_1 conduction-band minima at high electric fields in GaSb. For high-mobility semiconductors in the near infrared, the Faraday effect is practically independent of the momentum relaxation time, and its decrease with electric field can be related to carrier transfer between minima. An analyzer has been built with a minimum resolution of 3×10^{-3} deg. A decrease of 14% has been observed in the electron population of the Γ_1 valley at 1.1 kV/cm, which is in good agreement with calculated values. Influences of nonparabolic conduction-band and carrier heating on the Faraday effect are considered.

I. INTRODUCTION

Carrier transfer by high electric fields in many-valley semiconductors with nonequivalent conduction-band minima has been investigated several times in the past. Most of this work has been directed towards a better understanding of the conduction mechanism in GaAs, because of its practical application in Gunn-effect devices. One of the basic parameters in describing the high-field properties of many-valley semiconductors is the amount of carrier transfer between the minima. Experimental information about this quantity has been obtained either by observing the j-E characteristics[1] or the galvanomagnetic phenomena.[2–5] It is impossible, however, to evaluate directly from these methods the amount of electron transfer into the higher minima, since the measureable quantities represent the change with electric field of both the electron distribution and the relaxation time. The plasma frequency has been proposed as a test for intervalley transfer by several authors.[6,7]

In a recent letter[8] we introduced the infrared Faraday effect as an experimental method for studying carrier transfer and reported preliminary experimental results obtained on GaSb. For $\omega\tau \gg 1$ (ω = frequency of incident light, τ = momentum relaxation time), the Faraday rotation is practically independent of τ and of any change in τ due to the application of an electric field, so that the change in valley population can be obtained directly.

We report an experimental investigation of Faraday rotation in GaSb at 300 °K and its possible interpretations in terms of carrier transfer between the Γ_1 and L_1 conduction-band minima. We will also consider the influence of nonparabolic conduction bands as well as carrier heating. These effects are found to be small compared with the influence of carrier transfer.

II. EXPERIMENTAL

The experimental arrangement is shown schematically in Fig. 1 and is similar to the apparatus described by Craig *et al.*[9] Plane-polarized light from a HeNe laser operating at 3.39 μm was focused on the sample in a magnetic field. The analyzer could be rotated about 360° and consisted of two Ge flats oriented at the Brewster angle in the light

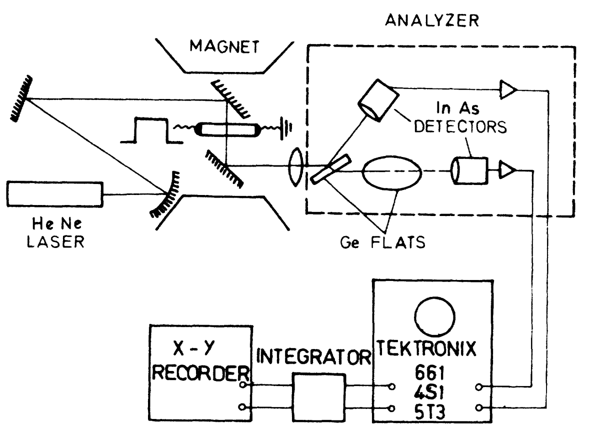

FIG. 1. Diagram of the experimental arrangement.

beam and rotated 90° against each other. When the plane of polarization of the beam is inclined at 45° against the plane of incidence of the Brewster flats, both detectors mounted in the path of the reflected beams receive the same signal. A change in the polarization changes the detector signals and the corresponding rotation is given by $\vartheta = \frac{1}{2}\arcsin(D/S)$, where D is the differential signal, and S the sum signal of the detectors. Applying a voltage pulse to the sample resulted in a change of the plane of the polarization, and the corresponding change in detector signal could be observed on a sampling oscilloscope followed by an integrator and an X-Y recorder. The integrator served to reduce the noise and to smooth the output signal of the oscilloscope. This was necessary because of the low repetition rate of the pulses (1 Hz). In this way a minimum resolution of 3×10^{-3} deg could be obtained by using a laser of 10 mW power.

The material used for the present investigation was single crystal n-type GaSb. Samples were quadrangular in shape ($1.45\times1.45\times5$ mm^3) and had two opposite faces (1.45×5 mm^2) polished. Contacts were soldered to the end faces, and high-voltage pulses were applied to the sample by means of a low-impedance (1 -Ω) pulse generator with a pulse length of 0.5 μsec and a repetition rate of 1 Hz, to minimize sample heating. Assuming adiabatic sample heating during a pulse, we arrive at a calculated rise of lattice temperature of 2.5° at a field strength of 1 kV/cm.

Due to the low energetic separation between the Γ_1 and the L_1 band ($\Delta = 0.1$ eV) both minima are occupied by electrons at 300 °K. The numbers of electrons in Γ_1 and L_1, and N_0 and N_1, respectively, are given by

$$N_0 = 4\pi\left(\frac{2m_0kT_e}{h^2}\right)^{3/2}\mathfrak{F}_{1/2}\left(\frac{E_F}{kT_e}\right), \tag{1a}$$

$$N_1 = 4\pi\left(\frac{2m_{1t}kT_e}{h^2}\right)^{3/2}4K^{1/2}\mathfrak{F}_{1/2}\left(\frac{E_F-\Delta}{kT_e}\right), \tag{1b}$$

T_e being the electron temperature (300 °K at Ohmic conditions) and E_F the Fermi energy. $\mathfrak{F}_{1/2}$ are Fermi integrals, m_0 and m_{1t} are the effective masses in Γ_1 and L_1, respectively, and $K = m_{1l}/m_{1t}$, the anisotropy coefficient of the L_1 minima. With the values of Table I, we obtain for zero electric field $N_0(0) = 0.46N$, where $N = N_0 + N_1 = 6.8\times10^{16}$ cm^{-3}.

By applying the well-known formulas for two-band conduction (e.g., Smith[10]), and from the measured Hall constant and the conductivity, together with the known value of the mobility ratio $b = \mu_0/\mu_1$, the listed values of N, $N_0(0)$, and $N_1(0)$, we have obtained μ_0, μ_1.

In Fig. 2, results are given for the observed decrease of the Faraday angle ϑ during application of a dc field at the sample up to 1.1 kV/cm. The contribution of multiple internal reflections to the

TABLE I. Constants for GaSb used in the numerical calculations.

Effective mass in Γ_1 at $k=0$ [a]	$m_{00}=0.047m$
Transverse effective mass in L_1 [b]	$m_{1t}=0.143m$
Anisotropy coefficient in L_1 [b]	$K=8.6$
Separation between Γ_1 and L_1 [b]	$\Delta=0.1$ eV
Mobility ratio between Γ_1 and L_1 [b]	$b=5.6$
Refractive index [c]	$n=4.05$
Total electron concentration [d]	$N=6.8\times10^{16}$ cm^{-3}
Electron concentration in Γ_1 [d]	$N_0(0)=3.1\times10^{16}$ cm^{-3}
Mobility in Γ_1 [d]	$\mu_0=3100$ cm^2/V sec
Mobility in L_1 [d]	$\mu_1=550$ cm^2/V sec

[a]Reference 11.
[b]Reference 12.
[c]Reference 13.
[d]Calculated values for the material of the present investigation.

Faraday angle ϑ and therefore also to $\Delta\vartheta$, has been investigated by Piller.[14] From his results we obtain

$$\vartheta'=\vartheta(1+2R^2e^{-\eta d}\cos4\vartheta') , \qquad (2)$$

where ϑ' is the observed and ϑ the single-pass angle of rotation, $R=(n-1)/(n+1)$ is the reflection coeffieient, d is the sample width, and η is the absorption coefficient. With η for free-carrier absorption[15] we obtain for our samples $\vartheta'=1.18\vartheta$. The full curve in Fig. 2 represents values which have been corrected for multiple reflections.

Results for the normalized conductivity as a function of electric field strength are given in Fig. 3.

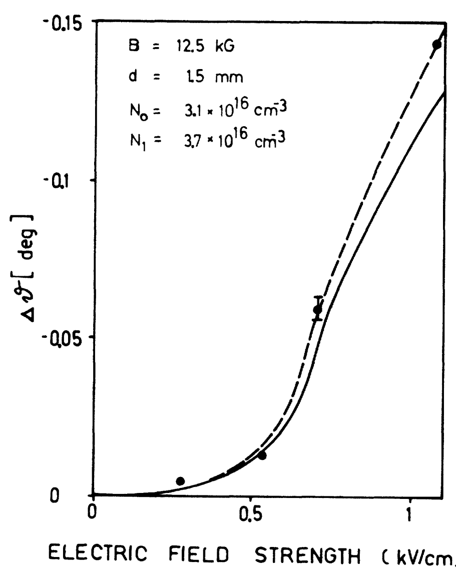

FIG. 2. Experimental results for the observed decrease in Faraday rotation (dashed line) and values corrected for multiple internal reflections (full line).

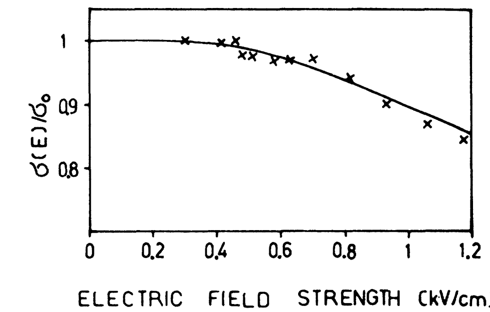

FIG. 3. Experimental results of the normalized conductivity (crosses) and calculated values (Ref. 4) (full line).

III. EVALUATION OF ΔN_0 FROM OBSERVED $\Delta\vartheta$

The contribution by free electrons to the Faraday effect is given by[16]

$$\vartheta=\pi/nc(\mathrm{Im}\sigma_- - \mathrm{Im}\sigma_+) ,$$

where n is the refractive index and $\sigma_\pm$ are the conductivities for left-hand and right-hand circulary polarized light. From this we obtain

$$\vartheta=\frac{Ne^2\pi d}{ncm_0}\,\frac{-2\omega_c\tau^2}{(1+i\omega\tau)^2+\omega_c^2\tau^2} , \qquad (3)$$

where $\omega_c=eH/m_0c$ is the cyclotron frequency and τ is the momentum relaxation time. For weak magnetic fields and $\omega\tau\gg1$, Eq. (3) may be approximated by

$$\vartheta=2\pi e^3NHd/nc^2m_0^2\omega^2 , \qquad (4)$$

which is independent of τ.

Equation (4) is a good approximation for the near infrared and for high-mobility semiconductors. For GaSb, with a mobility in Γ_1 of $\mu_0=3100=$ cm^2/V sec at 300 °K, we obtain $\omega\tau=43$ at $\lambda=3.39$ μm. Therefore, we expect that the Faraday effect is independent of τ and that a change in ϑ during application of an electric field represents the change in N_0. This is also justified by an estimation of the influence of $\tau(E)$ on ϑ, reported recently by Wood,[17] which we will discuss below.

In case of a many-valley semiconductor with a spherical central minimum and higher ellipsoidal minima, the Faraday rotation is given by[18]

$$\vartheta=\frac{2\pi e^3NHd}{nc^2\omega^2}\left(\frac{\alpha_0}{m_0^2}+\frac{\alpha_1}{m_{t1}^2}\,\frac{K+2}{3K}\right) , \qquad (5)$$

with $\alpha_0=N_0/N$ and $\alpha_1=N_1/N$.

It is therefore possible to obtain the population of the two valleys as a function of electric field from an experimental investigation of a change in ϑ, provided the band parameters of both minima are known. However, in most cases the effective masses in the higher minima are large compared to the central minimum, so that only electrons in the central minimum contribute significantly to the rotation, and an exact knowledge of the masses in the higher minima is not necessary. For GaSb, the ratio of the first to the second term in Eq. (5) is $20.5\,\alpha_0/\alpha_1$.

In order to calculate ϑ from Eq. (5) it is necessary to consider more carefully the value of m_0 to be used, since it enters quadratically. The most accurate values of m_0 have been derived from Faraday investigations at low temperatures where all electrons are in Γ_1.[11,19] In Ref. 11, a value of $m_0 = 0.048m$ has been given obtained at 20 °K. Correcting this value for multiple internal reflections, we arrive at $m_0 = 0.050m$. To obtain the effective mass at the bottom of the conduction band m_{00}, which is different from m_0 due to nonparabolicity, we start from the expression for $E(\vec{k})$ as given by Kane,[20] and get for small $\vec{k}$

$$\frac{1}{m_0} = \frac{1}{m_{00}}\left[1 - \frac{3kT_e}{E_g}\left(1 - \frac{2m_0}{m}\right)\right] . \tag{6}$$

A corresponding expression for degenerate material has been quoted by Piller.[21] From these equations we find that m_{00} is 6.3% smaller than the measured one in Ref. 11, that is $m_{00} = 0.047m$. Inserting this in Eq. (6), a value of $m_0(300) = 0.052m$ is obtained, and from Eq. (5), $\vartheta = 0.93°$ is calculated for the sample of Fig. 2.

With this value of ϑ and the observed change $\Delta\vartheta$, the corresponding change ΔN_0 has been calculated from Eq. (5) and is shown in Fig. 4.

Calculations for $N_0(E)$ and $\sigma_0/\sigma(E)$ have been performed according to the same model as reported recently,[4] and results are also given in Figs. 3 and 4.

IV. INFLUENCE OF OTHER EFFECTS ON DECREASE OF $\Delta\vartheta$

In Sec. III we have assumed that the oserved decrease in ϑ is exclusively caused by carrier transfer into L_1 minima. We will, therefore, estimate

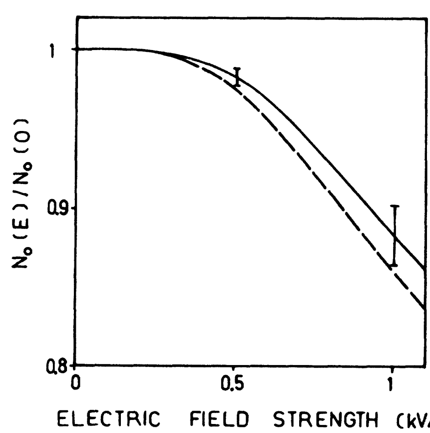

FIG. 4. Normalized decrease of Γ_1 population (full line) as obtained from the decrease in Faraday rotation (Fig. 2). The dashed line is calculated (Ref. 4).

the influence of other effects, especially those of the nonparabolicity of the conduction band and of the change of τ with applied electric field.

Simple calculations[4] give an increase of the electron temperature of 30° at a field of 1.1 kV/cm. The associated increase in m_0 according to Eq. (6) causes a decrease in ϑ of 2%. Compared with $\Delta\vartheta = 15\%$ at 1.1 kV/cm, this is a relatively small effect in GaSb. However, in semiconductors like GaAs where T_e increases to about 600 °K before electron transfer starts, the influence of the nonparabolicity will be dominant in the range below the Gunn-effect threshold.

The influence of a decrease in momentum relaxation time with applied electric field has been calculated by Wood[17] by considering only scattering by acoustical phonons. Although this is not the dominant scattering mechanism in GaSb, we may obtain an upper limit for the expected change in ϑ from his results, where $\vartheta(E)/\vartheta_0$ is given by

$$\frac{\vartheta(E)}{\vartheta_0} = \frac{1 - 2q^{-1}R_2(p)}{1 - 15/2q} , \tag{7}$$

with $q = \omega^2\tau_0^2$ and $p = \frac{3}{16}\pi\mu_0^2E^2/u^2$. u is the longitudinal sound velocity, and the subscript 0 refers to zero electric field. The function R_2 has been tabulated by Wood. From Eq. (7) a $\vartheta(E)/\vartheta_0 = 0.99$ is obtained for GaSb at 1 kV/cm. The actual decrease in ϑ is expected to be still smaller since the change in mobility and therefore in τ with electric field is very small in GaSb. This can be concluded from the good agreement between observed $\sigma(E)$ and the calculated values which are based on a constant mobility.

V. CONCLUSIONS

It has been shown that from an experimental investigation of the infrared Faraday effect the carrier transfer in many-valley semiconductors can be directly obtained. As a consequence of the larger difference in effective masses between the different minima, and due to the quadratic dependence of ϑ on $1/m_0$, an exact knowledge of the effective masses in the higher minima will not be necessary in most cases. Spurious effects may arise from the influence of nonparabolic conduction bands and changes in momentum relaxation time with electric field. The latter effect will be negligible in the high-mobility semiconductor in the near infrared. Nonparabolicity, however, may become the dominant effect in materials which exhibit electron transfer only at high electron temperatures. The observed electron transfer in GaSb agrees well with calculated values reported, recently.[4]

ACKNOWLEDGMENTS

We want to express our appreciation to Professor K. Seegar for initiation of this experiment and to W. Jantsch for stimulating discussions and for performing some of the numerical calculations.

*Work supported by Fonds zur Förderung der Wissenschaft, Austria.

[1]E.g., J. G. Ruch and G. Kino, Appl. Phys. Letters 10, 40 (1967).
[2]A. Zylberstejn and J. B. Gunn, Phys. Rev. 157, 668 (1967).
[3]G. A. Acket, Phys. Letters 25A, 374 (1967).
[4]H. Heinrich and W. Jantsch, Phys. Status Solidi 38, 225 (1970).
[5]H. Heinrich, K. Lischka, and M. Kriechbaum, Phys. Rev. B 2, 2009 (1970).
[6]M. A. Omar, Phys. Rev. 171, 925 (1968).
[7]H. K. Kar and M. N. Mukherjee, Phys. Letters 30A, 355 (1969).
[8]H. Heinrich, Phys. Letters 32A, 331 (1970).
[9]J. S. Craig, R. F. Gribble, and A. A. Dougal, Rev. Sci. Instr. 35, 1501 (1964).
[10]R. A. Smith, *Semiconductors* (Cambridge U. P., Cambridge, England, 1964).
[11]G. Bordure and F. Gustavino, Compt. Rend. 267, 860 (1968).
[12]C. Y. Liang, J. Appl. Phys. 39, 3866 (1968).
[13]*American Institute of Physics Handbook*, edited by D. E. Gray (McGraw-Hill, New York, 1963).
[14]H. Piller, J. Appl. Phys. 37, 763 (1966).
[15]F. R. Kessler, Phys. Status Solidi 5, 3 (1964).
[16]M. Balkansky and E. Amzallag, Phys. Status Solidi 30, 407 (1968).
[17]V. E. Wood, J. Appl. Phys. 40, 3740 (1969).
[18]I. P. Ipatova, P. E. Kazarinov, and A. V. Shubashiev, Fiz. Tverd. Tela 7, 2129 (1965) [Soviet Phys. Solid State 7, 1714 (1966)].
[19]H. Piller, J. Phys. Chem. Solids 24, 425 (1963).
[20]E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957).
[21]H. Piller, in *Proceedings of the International Conference on the Physics of Semiconductors, Moscow, 1968* (Nauka Publishing House, Leningrad, 1968), p. 353.

PHYSICAL REVIEW B VOLUME 3, NUMBER 2 15 JANUARY 1971

High-Field Transport in the Three-Valley Conduction Band of Gallium Antimonide*

W. Jantsch and H. Heinrich
Institut für Angewandte Physik der Universität, A-1090 *Vienna, Austria*
and Ludwig-Boltzmann Institut für Festkörperphysik, Vienna, Austria

(Received 27 July 1970)

The j-E characteristics of Te-doped GaSb have been measured up to a field strength of 18 kV/cm at 300 °K and up to 7.5 kV/cm at 77 °K. Results for the longitudinal magnetoresistance and the Hall constant at 300 and 77 °K up to a field strength of about 7 kV/cm are given. Avalanche breakdown was observed at a field strength above 7 kV/cm, and the electron-hole pair generation rate at 300 °K was determined. Calculations based on a three-band model are compared with the measurements. For high-field strengths the influence of the highest X_1 minimum has to be taken into account to obtain agreement between experimental and calculated results. Attempts have been made at an experimental realization of the negative differential resistance (NDR) predicated by Zaitsev and Zvezdin due to virtual states below the L_1 minimum. The effect, although observable, has been found to be not sufficient to produce NDR.

I. INTRODUCTION

In a recent paper[1] we reported measurements of the electrical conductivity and the longitudinal magnetoresistance of GaSb at high electric fields. For calculation, a two-band model was used, in which we considered carrier transfer from the lowest conduction-band minimum (Γ_1) at the center of the Brillouin zone to the four minima (L_1) along the $\langle 111 \rangle$ directions in k space lying 0.1 eV above the Γ_1 minimum.[2] We now want to discuss a more detailed investigation of high-field galvanomagnetic properties of GaSb, and we present calculations which take into account the third type (X_1) of conduction-band minima, lying at the zone boundaries along the $\langle 100 \rangle$ directions, 0.315 eV above the Γ_1 minimum.[3] Hilsum and Rees[4] have considered the three-valley semiconductors for high-efficiency Gunn devices, and a Gunn effect has been reported for $Ga_xIn_{1-x}Sb$ alloys.[5] Therefore, it appears to be of interest to study the high-field behavior of the GaSb component of this system in connection with the proposed three-valley effect.

It is well known (see Butcher and Fawcett[6]) that according to a simple criterion no negative differential resistance (NDR) will be obtained when the energy separation of the lowest two sets of minima is less or comparable to $4kT$. This is obviously fulfilled for GaSb at 300 °K, and no NDR has been observed because of the thermal population of the L_1 minima. This offers the interesting possibility of studying electron transfer without experimental